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Evolution of optical spectral index and variability properties of S5 0716+714 *

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Abstract We analyze the spectral variability and spectral evolution in the optical energy region by using multiband (BVRI) optical observations of S5 0716+714 spanning 1994 to 2005. The spectrum hardens when the source becomes brighter, which is consistent with general BL Lac objects. The spectral evolution parameter implies that the spectral variability is small in optical bands over 10 years. A simple model representing the variability of a synchrotron component can explain the spectral changes. In addition, we employ the z-transformed discrete correlation function (ZDCF) to analyze the optical multiband flux correlation. The long-term light curve behavior reveals that the variability time scales are 3.5 yr in the B-band, 3.3 yr in the V-band, 3.4 yr in the R-band and 3.5 yr in the I-band. The time lags between any two optical bands were not found when considering statistical errors.

Key words: BL Lacertae objects: general — galaxies: active — BL Lacertae objects: individual (S5 0716+714)

1 INTRODUCTION

Blazars, including flat spectrum radio quasars (FSRQs), and BL Lac objects, are well known as highly variable sources characterized by nonthermal emission that dominates radio to high-energy TeV gamma-ray regions. The blazars exhibit flux variations on different time scales, varying from a few minutes to many years at all accessible wavelengths of the electromagnetic spectrum. Generally, there are three classes of variability in blazars: intra-day or intra-night variability (IDV) or microvariability, short-term variability and long-term variability. Usually, IDV has variations in flux of up to a few tenths of a magnitude over one observation night or less, while a few magnitudes of variations are seen in short-term and long-term variability. The time scales of short-term and long-term variability are from weeks to several months and several months to years, respectively (see review in Gupta et al. 2008a,b, 2009). It is widely accepted that the variations recognizable in blazar light curves have long-term and possibly periodic variability (Villata et al. 2002; Dai et al. 2006). Some particular objects have been claimed to display periodicity in their light curves over a variety of timescales (e.g. Jurkevich 1971; Sillanpää et al. 1988; Webb et al. 1988; Kidger et al. 1992; Liu et al. 1995; Fan et al. 1997, 1998, 1999, 2002; Lainela et al. 1999; Fan & Lin 2000; Lin 2001; Gupta et al. 2009).

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The optical flux variations in blazars are frequently associated with changes in the spectral shape. This can be revealed by analyzing the magnitude color index or the flux spectral index. A study of the relationship between the optical spectral variability and the brightness variation implies that there are two tendencies for the correlation of color index and magnitude: (1) for BL Lacs, the spectrum becomes steeper when the flux decreases and flatter when it increases; (2) FSRQs have an opposite trend (see Dai et al. 2009 and references therein). The different trends in color index variations with brightness in blazars imply the existence of two varying modes, namely, larger flux variations with smaller spectral changes and the inverse effect. These two varying modes may result if the object is brightening, fading, or in a quiescent state. At a low flux level, small changes in flux correspond to large changes in the spectral slope, while much less pronounced spectral changes correspond to a high brightness state. In both cases, the object reddens when it brightens (Clements et al. 2003; Ramírez et al. 2004). The rate of the spectral slope change is different for different rising/decaying parts of the light curves (Papadakis et al. 2003). The variation dependence of spectral changes is likely caused by different physical mechanisms. The optical spectral variations in 8 blazars and 42 QSOs showed that blazars have smaller spectral variability than QSOs. This difference is a consequence of the different emission mechanisms in the optical band: synchrotron in the case of blazars, and thermal hot spots on the accretion disk in the case of QSOs (Trevese & Vagnetti 2002; Vagnetti et al. 2003).

S5 0716+714 is classified as a BL Lac object because of its featureless optical spectrum and high linear polarization (Biermann et al. 1981). The synchrotron peak of the spectral energy distribution (SED) of S5 0716+714 is located in the optical band and is, therefore, classified as an LBL (Nieppola et al. 2006). Nilsson et al. (2008) derived a redshift of $z = 0.31 \pm 0.08$ by optical imaging of the underlying galaxy. The γ-ray flux with an average flux ($E > 100\,\mathrm{MeV}$) of $(97 \pm 15) \times 10^{-8}\,\mathrm{photons\,cm^{-2}\,s^{-1}}$ of S5 0716+714 at a significance level of 9.6σ was detected by AGILE (Chen et al. 2008). The MAGIC group observed a very high energy γ-ray excess with a significance of 5.8σ in the high optical state in November 2007 and April 2008, which suggests a possible correlation between the VHE-ray and optical emissions (Anderhuba et al. 2009). The multicolor near infra-red IDV was studied in Gupta et al. (2008a). They found variability amplitudes of 32.6%, 20.5% and 18.2% in the J, H, and K bands, respectively, implying larger variations at higher frequencies. Periodic oscillations of 25–73 min in the optical band of the blazar S5 0716+714 were found (Chatterjee et al. 2008; Gupta et al. 2009).

In recent years, the correlation of the variability in different energy regions has been widely studied. Villata et al. (2000) found an upper limit to the possible delay between the B and I variations (10 min). Qian et al. (2000) obtained an upper limit in the time lag of 0.0041 d (about six minutes) between the V and I bands. Wu et al. (2005) found that no apparent time lag was observed between the V and R-band variations. Wagner et al. (1996) presented an extensive study of the rapid variability in S5 0716+714 in various energy bands, from radio to X-rays, and found a close correlation through the optical-radio segment, and possibly between the optical and X-ray bands. Raiteri et al. (2001, 2003) discussed that the broad radio outbursts do not correspond in time to the faster optical ones. Furthermore, the cross-correlation analysis showed a weak correlation with long time lags. The behavior of the optical and radio light curves is quite different. Faster variations often imply spectral changes caused by a different physical mechanism.

In this work, we focus mainly on the evolution of the optical spectral index of S5 0716+714. In addition, we have investigated the properties of long-term periodic variability and the variation correlation between any two optical bands. In Section 2, we present the multi-color optical light curves. In Section 3, we investigate the evolution of the optical spectral index α and spectral variability parameter β. In Section 4, we study evidence of the correlation and periodicity of S5 0716+714 in the optical multi-band by using the z-transformed discrete correlation function (ZDCF) method. The discussions and conclusions are in Section 5.

2 THE LONG-TERM BEHAVIOR OF S5 0716+714

Extensive observations and searches for the variability in blazars have been made for about 20 years, since the first convincing optical IDV in a blazar was reported by Miller et al. (1989). Almost all blazars are reported with variability on different time scales ranging from a few minutes to several years (see review in Gupta et al. 2008a,b). S5 0716+714 is one of the most intensively monitored objects in our long-term optical campaign. Our observations were performed using the 1.02-m telescope at Yunnan Observatory (YAO) and the 1.56-m telescope at Shanghai Observatory (SHAO) from 2004 to 2005. The observation log is shown in Table 1. We made 19 nights of observations in the B, V, R and I bands. Typical photometric uncertainties range from 0.01 to 0.03 mag rms. The details of the observations and data reduction will be reported in Dai et al. (2009) (in preparation). In addition, we compiled the available multi-color (B, V, R and I bands) observational data from the literature (Ghisellini et al. 1997; Qian et al. 2002; Raiteri et al. 2003; Montagni et al. 2006). In total, we have quasi-instantaneous observation data for S5 0716+714 in the B, V, R and I bands spanning 1994 to 2005. Figure 1 shows the flux variations in the optical band. Four major optical outbursts have been reported for this source: at the beginning of 1995, in late 1997, at the end of 2000, and in fall 2001 (see details in Raiteri et al. 2003). On 1999 February 21 (around JD 2451546), the source reached a high state both in the V and R bands (12.48 in V, 12.08 in R) (Qian et al. 2002). The variabilities in each band have a consistent trend. Our observations are shown in the last part of Figure 1.

Table 1 Observation Log of PKS 0716+714

Observation time	B filter	V filter	R band	I band	Telescope
2004 Jan. 11		24	24	23	YAO
2004 Jan. 13		16	14	17	YAO
2004 Apr. 20			12	12	YAO
2004 Apr. 21			12		YAO
2005 Feb. 4	6	5	17	7	YAO
2005 Feb. 5	18	20	20	20	YAO
2005 Feb. 15	21	20	19	20	YAO
2005 Feb. 16	24	24	24	24	YAO
2005 Feb. 17	21	21	21	21	YAO
2005 Feb. 18	20	20	20	20	YAO
2005 Feb. 27	5	5	4	5	YAO
2005 Mar. 1	3	3	3	3	YAO
2005 Apr. 5		2	2	2	YAO
2005 Apr. 6	8	9	10	10	YAO
2004 Nov. 15			28		SHAO
2004 Nov. 17			29		SHAO
2005 Jan. 16			21	28	SHAO
2005 Jan. 19			30	32	SHAO
2005 Mar. 17				3	SHAO

3 THE OPTICAL SPECTRUM AND ITS EVOLUTION

The relationship between optical spectral variability and brightness variation is important for constraining the emission model for different blazars. Generally, there are two tendencies present in the correlation of color index and magnitude: (1) for BL Lacs, the spectrum becomes steeper when the flux decreases and flatter when it increases; (2) FSRQs have the opposite trend. This may indicate that physical conditions in these two populations are different. So, long term simultaneous or quasi-simultaneous multi-band observations are helpful to investigate spectral properties and their evolution both in terms of their large variation state and quiescent state.

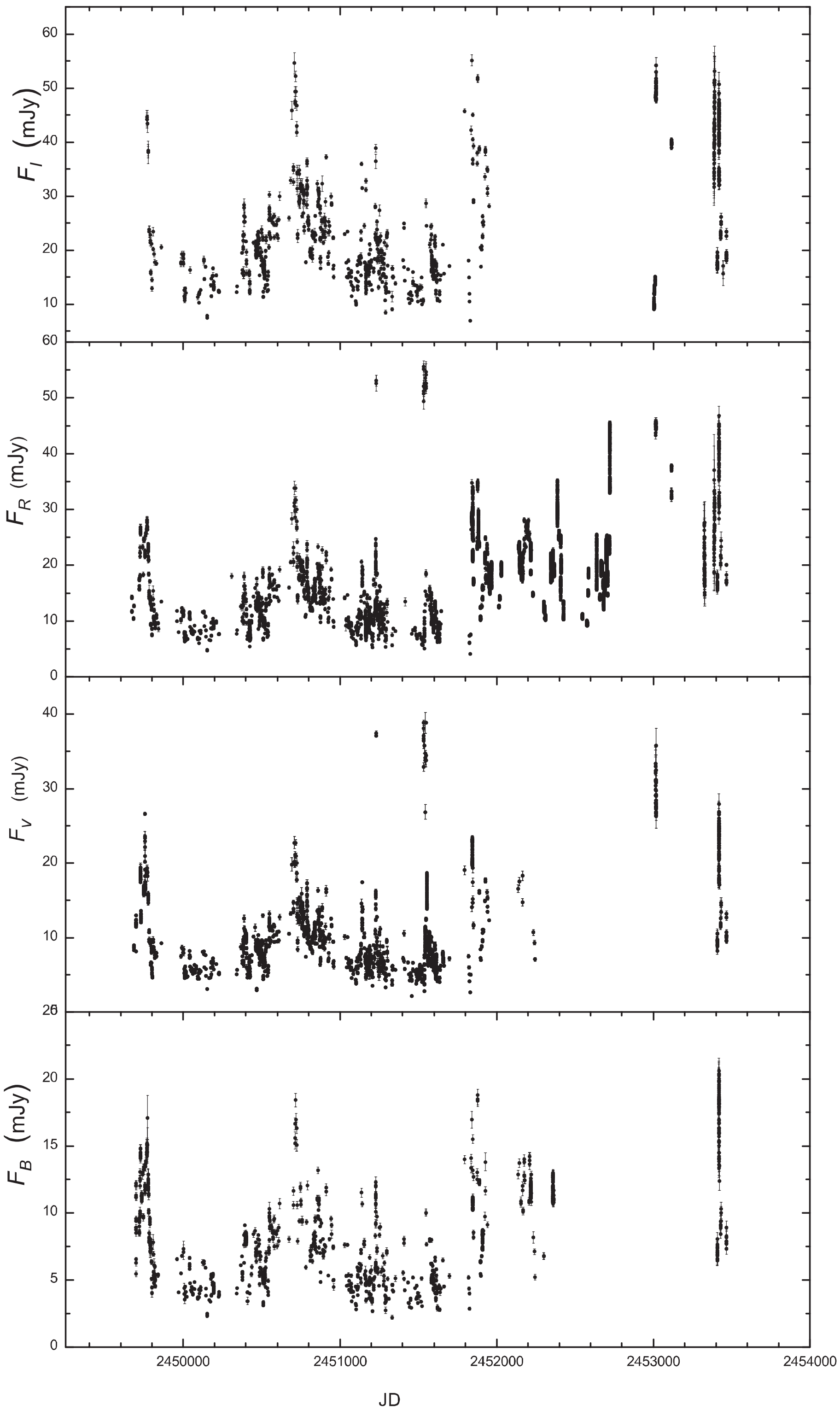

Fig. 1 Long-term variabilities of S5 0716+714 in the B, V, R and I bands.

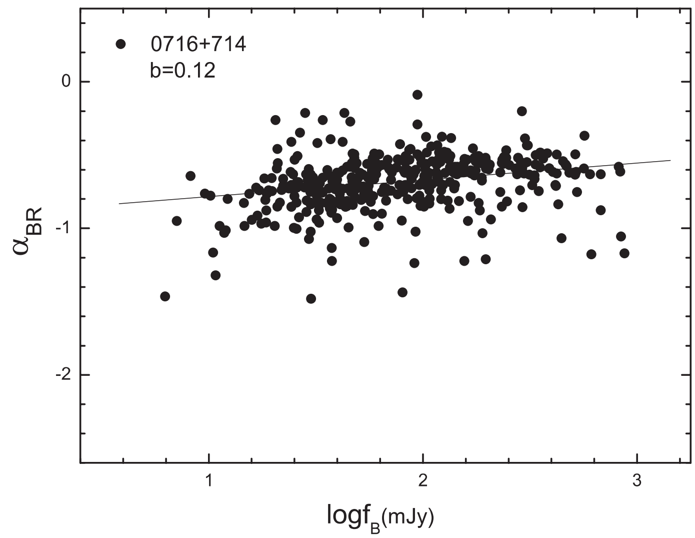

Fig. 2 Spectral index of PKS 0716+714. The solid line represents the regression line, $r = 0.26, p < 0.00014$, and $N = 407$.

The spectral property could be described by the instantaneous slope, e.g. the spectral index α_{BR}. By using the multi-band optical data described in Section 2, we could calculate α_{BR} by using the following equation (Trevese & Vagnetti 2002; Vagnetti et al. 2003).

$$\alpha_{BR} = \frac{0.4[(B-R)+(B_0-R_0)]}{\log(\lambda_B/\lambda_R)} - 2, \tag{1}$$

where B_0 and R_0 are the zero points of magnitudes, and λ_B and λ_R are the relatively effective wavelengths of the two photometric bands (Cox 2000).

The spectral index of α_{BR} is shown in Figure 2. A linear fit was drawn and the linear Pearson correlation coefficient $r = 0.26$ suggests a weak correlation between spectral index and flux. The relationship of $\alpha_{BR} - \log f_{\nu B}$ implies that the source brightens when the spectrum becomes flat. This spectral variation trend is consistent with that of BL Lacs.

In order to quantify the spectral evolution, we calculate the parameter β which represents the change of spectral slope per unit variation of log flux as a function of the rest-frame time lag τ_{ij}. This spectral parameter is a very sensitive indicator of spectral changes. Following the suggestion of Vagnetti et al. (2003), we limit the calculation to $|\log f_{\nu_B}(t_j) - \log f_{\nu_B}(t_i)| > 0.03$.

$$\beta_{ij} \equiv \beta(\tau_{ij}) \equiv \frac{\alpha_j - \alpha_i}{\log f\nu_B(t_j) - \log f\nu_B(t_i)} \tag{2}$$

$$\tau_{ij} \equiv \frac{(t_j - t_i)}{(1+z)}, i, j = 1, N \tag{3}$$

The calculated value β represents the change of spectral slope α_{BR} with the variation of flux. The relationship between spectral changes with time scale β-τ is shown in Figure 3. The mean values of β_{ij} in bins of 300 d are also shown (solid circles). The errors represent the mean standard deviation. In Figure 3, one can see whether spectral changes are different on different time scales. Our results show that there are no evident systematic trends of β as a function of τ within 2500 d, i.e. small spectral variability. This is consistent with the results of Vagnetti et al. (2003), which means that the source S5 0716+714 has the spectral evolution parameters of BL Lacs.

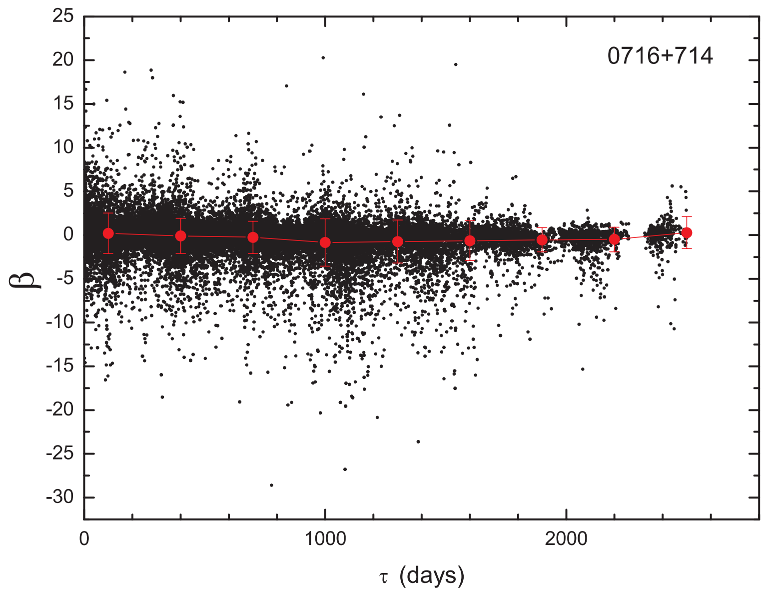

Fig. 3 Relation between spectral evolution parameter β and time delay τ. The solid circles show the average values and errors.

4 THE LONG-TERM VARIABILITY PROPERTY OF S5 0716+714

4.1 z-transformed Discrete Correlation Function (ZDCF)

In this section, we apply the ZDCF method to analyze the correlation of the optical variation by using the observation in the B, V, R, and I bands. The ZDCF is much more efficient than other cross-correlation functions (CCFs) when dealing with sparsely sampled light curves (see Alexander 1997 for details).

The ZDCF approximates the bin's distribution by a bi-normal distribution, for which Fisher's z-transform (Fisher 1921) formula is defined as follows:

$$z = \frac{1}{2}\log\left(\frac{1+r}{1-r}\right), \qquad r = \tan hz, \tag{4}$$

which is roughly normally distributed with a known mean, $\bar{z}(\rho)$ and variance, $s_z^2(\rho)$. These are estimated by $\bar{z}(r)$ and $s_z^2(r)$. The bin's ZDCF estimate is then

$$r_{zdcf}(\tau) = r^{+[\tan h(\bar{z}+s_z)-r]}_{-[r-\tan h(\bar{z}-s_z)]}. \tag{5}$$

The data bin is taken with equal population, rather than with equal $\Delta\tau$. The convergence of the z-transform requires a minimum of $n_{\min} = 11$ points per bin. As a result of equal population binning, the bias only depends on $n_{\min}$ and not on the number of observations. Nevertheless, the ZDCF method can provide an uncertainty in the lag without interpolation. This is an advantage for analyzing heterogeneous samples of unequally sampled light curves (LCs) (see also Gupta et al. 2008c).

Table 2 ZDCF Autocorrelation Results in the B, V, R and I Bands

Band	ZDCF (d)
B	$1282^{+22.96}_{-5.28}$
V	$1238^{+20.52}_{-4.48}$
R	$1266^{+30.19}_{-6.558}$
I	$1282^{+21.24}_{-5.515}$

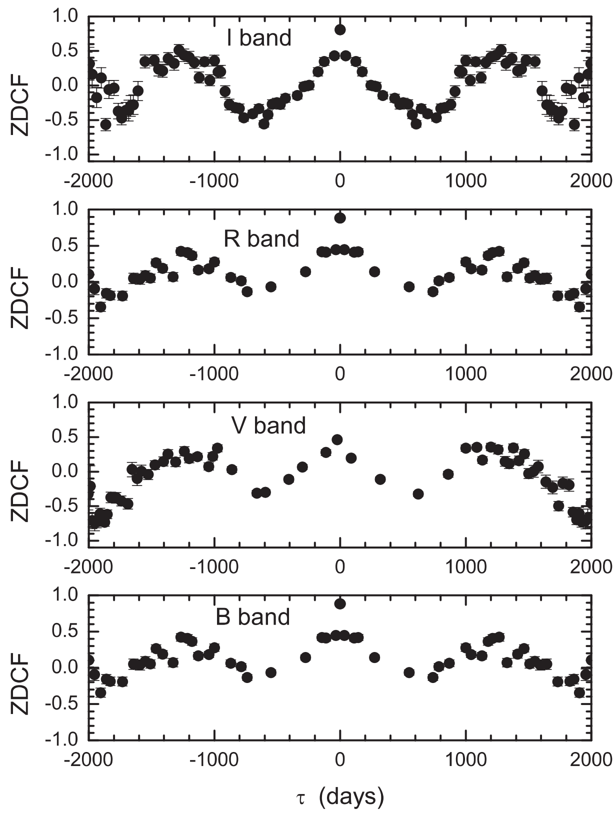

Fig. 4 ZDCF autocorrelations of flux in the B, V, R and I bands.

4.2 The Optical Multiband Correlation Analysis

Although short-term optical variability (hour scale) is now a well-established phenomenon for blazars, its relationship to the long-term variability remains unclear. So, we need to search for characteristic time scales of variability for S5 0716+714 in the optical band. According to the ZDCF method discussed in Section 4.1, we calculate autocorrelation and cross-correlation in the B, V, R, and I bands. The optical ZDCF autocorrelation is shown in Figure 4. The autocorrelation results are listed in Table 2.

In Figure 4, we found significant but wide peaks distributed from 1238 to 1282 d. These peak values can thus be regarded as characteristic time scales of optical variability for S5 0716+714. The possible periods in the B, V, R and I bands are listed in Table 2.

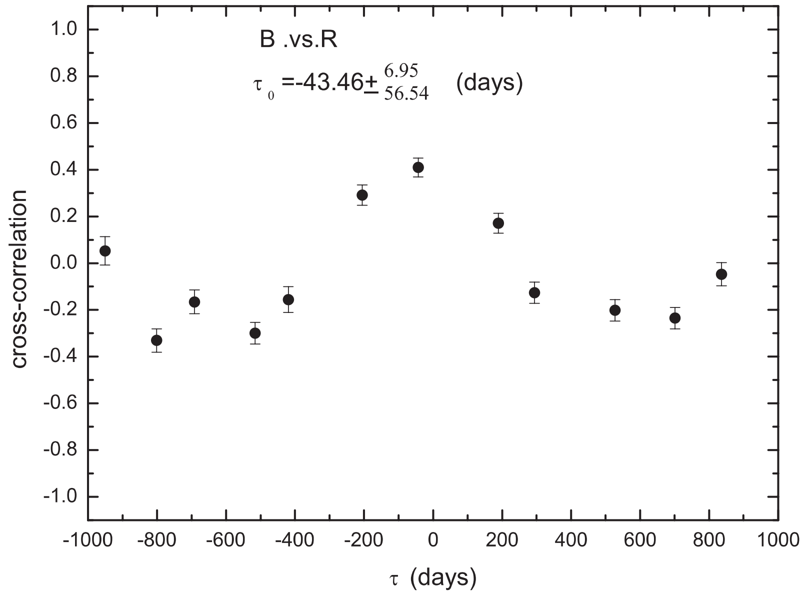

Fig. 5 ZDCF cross-correlations between the fluxes of the B and R bands.

The cross-correlation between any two bands would reveal the time lags in different energy bands. Our cross-correlation results of ZDCF analysis could not find any time lag between any two optical bands. Figure 5 shows the flux cross-correlation between the B and R bands. The peak is located at –43.46 d which suggests that the emission of the B band leads that of the R bands. However, the error of time delay is large, reaching 56.54 d. So, the time delay of two optical bands cannot be confirmed. The reason for this is that the time resolution of our ZDCF analysis on long-term variability is larger than that of observation. However, Villata et al. (2000) found that an upper limit to the possible delay between B and I variations (10 min) has been fixed owing to the high quality and density of part of the data set. Qian et al. (2000) obtained an upper time lag limit of 0.0041 d (about 6 min) between the V and I bands using the same method. Raiteri et al. (2003) found a weak correlation between optical and radio emissions by using discrete correlation function (DCF) analysis.

5 CONCLUSIONS

In the framework of current synchrotron emission models, spectral hardening is expected to be correlated with a luminosity increase in the optical band (see, e.g., Kirk et al. 1998). To investigate the spectral evolution and variability properties of S5 0716+714, we calculated the optical spectral index and evolution parameter β.

In Figure 2, a linear fit with a slope of 0.12 ± 0.02 and a linear Pearson correlation coefficient $r = 0.26$ suggest a weak positive correlation between spectral index and flux. This implies that the spectrum becomes flatter when the source is brighter. This spectral change trend is consistent with the general sense of variation of BL Lacs, that is, the spectrum becomes flat when the source is brighter (see, e.g., Massaro et al. 1996; Ghisellini et al. 1997; Clements & Carini 2001; D'Amicis et al. 2002; Villata et al. 2004; Papadakis et al. 2007).

To constrain physical models of variability, one considers spectral evolution, that is, spectral variation on different time-scales. In Figure 3, the relationship between the spectral evolution parameter β and time lag τ_{ij} is shown. The quantity β represents the change of spectral slope per unit variation of log flux as a function of the rest-frame time lag τ_{ij}. The average values of β, for example, in bins of time lag τ are important to constrain physical models of variability. For $\tau \leq 300\,\mathrm{d}$, there are no evident systematic trends in β as a function of τ. A less noisy index could be defined by taking the average of β during the first 300 d. Then, we would conclude that the spectral variability of S5 0716+714 is small, and the change in time scales is not less than 300 d.

Long-term trends are visible in the optical light curves. Statistical analysis by means of ZDCF suggests that the long-term trends may have periodic variability on time scales of $1282^{+22.96}_{-5.28}$ d, $1238^{+20.52}_{-4.48}$ d, $1266^{+30.19}_{-6.55}$ d, and $1282^{+21.24}_{-5.51}$ d in the B, V, R, and I bands, respectively. A $\sim$3.3-yr time scale variation was found in Raiteri et al. (2003) by applying a number of statistical tools, such as the Discrete Fourier Transform (DFT), the Discrete Correlation Function (DCF), and the Structure Function (SF).

In general, the variability of the blazar is strong in every band on both long and short time scales. The flux variations at lower frequencies are delayed with respect to those at higher frequencies. The large amplitude of gamma-ray variability with respect to that in the optical band favors a synchrotron self-Compton process (SSC) explanation for S5 0716+714 (Chen et al. 2008). The time lag may be explained by the jet model. In the homogeneous model, where the radiation is produced in a single homogeneous blob relativistically moving at a small viewing angle, time lags are interpreted in terms of electron cooling time scales. In the inhomogeneous jet model, the higher synchrotron frequencies are emitted from the inner, denser parts of the jet, while the lower ones are emitted from more external regions. The time lag is a measure of the distance between emitting regions in the jet (Raiteri et al. 2003). In this case, the optical emissions of different bands may originate from the same region or from the two nearest regions. Thus, the time lags in the optical bands would be short or even have null time lags. However, this does not exclude the effect of observed time resolution. Therefore, very dense monitoring with high precision data is needed to further check optical lags, as well as the trends in the short-term spectral behavior of this source.

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